AEIC'95

AL-AZHAR Engineering Fourth
International Conference
December 16-19,1995

المؤتمـــر العلمى الدولى الرابــع
كلية الهندسة - جامعة الأزهـــر
من ٢٣ إلى ٢٦ رجـــب ١٤١٦هـ
الموافق١٦ إلى١٩ ديسمبر١٩٩٥م

THE INFLUENCE OF MUD WEIGHT AND ORIENTATION ON THE STABILITY OF INCLINED BOREHOLES

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ABSTRACT

The Linear-Elastic solution (Kirsch solution) was used to study the effect of mud weight and orientation on the stability of inclined boreholes. It was found that, higher mud weights are required to maintain the stability of inclined boreholes. Boreholes drilled parallel to the minimum horizontal principal in-situ stress was found to be more stable compared to those drilled parallel to the maximum horizontal principal in-situ stress. Mohr-coulomb failure criterion was used in conjunction with the Linear-Elastic solution to predict the mechanical stability of inclined boreholes.

KEYWORDS

Borehole, Horizontal well, Inclination, Mud weight, Linear-Elastic, In-situ stresses.

NOMENCLATURE

P_p	=	Formation Pore Pressure.
P_w	=	Mud hydraulic pressure (wellbore pressure).
σ_H	=	Maximum Horizontal in-situ principal stress.
σ_h	=	Minimum Horizontal in-situ principal stress.

σ_v = Vertical principal in-situ stress.

$\sigma_x, \sigma_y, \sigma_{zz}$ = Transformed Principal in-situ stresses.

$\sigma_r, \sigma_\theta, \sigma_z$ = Induced radial, hoop and axial stresses.

σ = Total stress.

$\bar{\sigma}$ = Effective stress.

$\tau_{r\theta}, \tau_{\theta z}, \tau_{rz}$ = Induced Shear stresses.

$\tau_{xy}, \tau_{yz}, \tau_{zx}$ = Shear stresses in Cartesian coordinates.

θ = Angular position around the borehole.

α = Borehole inclination (w.r.t. vertical).

β = Borehole orientation (w.r.t azimuth).

ν = Formation Average Poisson's ratio.

INTRODUCTION

The benefits that come from drilling high angle and horizontal wells such as achieving high flow rates and reducing gas and water coning have been well documented [1]. Wellbore stability is controlled by in-situ stress state, rock strength, shale swelling, well geometery, well orientation and wellbore pressure balance (mud pressure minus pore fluid pressure). The influence of well orientation is often over-looked or minimized during the early stages of reservoir apprasial and development. In weak formations, small increase in the effective vertical stress due to pore pressure depletion can significantly impact drilling and completion operations [2-3]. This impact increases with increasing well angle. Therefore, rock mechanics modelling should be used to asses the risks associated with drilling high angle wells and the results can be used to determine the appropreate mud weights and borehole orientation to maintain hole stability.

MODEL FORMULATION

Formations can be classified as: normally stressed or tectonically stressed. In a normally stressed regions, the maximum in-situ stress is vertical and is equal to the overburden stress. In addition, the other two in-situ stresses, located in the horizontal plane, are equal or nearly equal. For well compacted and cemented formations, the overburden stress varies linearly with depth, with a gradient of approximately 2.1 kPa/m (1psi/ft). Tectonic stresses include all stress conditions which are not considered normally stressed. Tectonically active regions are often associated with areas having active faults, salt domes, or foot hills. In tectonically active areas, the principal in-situ stresses are not necessarily oriented in the horizontal and vertical directions, but they may be rotated through significant angles. In addition, the magnitudes of the three in-situ stresses are usually different. The ease with which the borehole instability can be computed is highly dependent on the stress-strain behaviour commonly chosen for modelling the formation response to loading. The most common behaviour assumed is that the formation is homogeneous, isotropic, and linear-elastic (HILE). This allows the stresses to be determined from a set of fairly simple equations. Other behaviour models generally necessitate a numerical approach.

Consequently a linear elastic analysis is the most common approach due to its ease of application. Also, more complex models frequently suffer from an extensive list of input parameters, many of which cannot be realistically determined. The equations required to compute the redistributed (induced) stress state is called the Kirsch solution. For a HILE formation, the solution is as follows [4-5]:

$$\sigma_r = P_w \qquad \text{...(1.a)}$$

$$\sigma_\theta = \left[\sigma_x + \sigma_y - P_w\right] - 2\left[\sigma_x - \sigma_y\right]\text{Cos}2\theta - 4\tau_{xy}\ \text{Sin}2\theta \qquad \text{...(1.b)}$$

$$\sigma_z = \sigma_{zz} - 2\nu\left[\sigma_x - \sigma_y\right]\text{Cos}2\theta - 4\nu\tau_{xy}\ \text{Sin}2\theta \qquad \text{...(1.c)}$$

$$\tau_{r\theta} = \tau_{rz} = 0 \qquad \text{...(1.d)}$$

$$\tau_{\theta z} = 2\left[-\tau_{zx}\text{Sin}\theta + \tau_{yz}\text{Cos}\theta\right] \qquad \text{...(1.e)}$$

$$\bar{\sigma} = \sigma - P_p \qquad \text{...(1.f)}$$

The in-situ principal stresses in the case of deviated hole can be transformed to the direction of the hole by using the following set of equations [5]:

$$\sigma_x = \sigma_H \text{Sin}^2\beta + \sigma_h \text{Cos}^2\beta \qquad \text{...(2.a)}$$

$$\sigma_y = \text{Cos}^2\alpha\left[\sigma_H \text{Cos}^2\beta + \sigma_h \text{Sin}^2\beta\right] + \sigma_v \text{Sin}^2\alpha \qquad \text{...(2.b)}$$

$$\sigma_{zz} = \text{Sin}^2\alpha\left[\sigma_H \text{Cos}^2\beta + \sigma_h \text{Sin}^2\beta\right] + \sigma_v \text{Cos}^2\alpha \qquad \text{...(2.c)}$$

$$\tau_{xy} = \text{Cos}\alpha\ \text{Sin}\beta\ \text{Cos}\beta\left[\sigma_H - \sigma_h\right] \qquad \text{...(2.d)}$$

$$\tau_{yz} = \text{Sin}\alpha\ \text{Cos}\alpha\left[\sigma_v - \sigma_H \text{Cos}^2\beta - \sigma_h \text{Sin}^2\beta\right] \qquad \text{...(2.e)}$$

$$\tau_{zx} = \text{Sin}\alpha\ \ \text{Sin}\beta\left[\sigma_h - \sigma_H\right]\text{Cos}\beta \qquad \text{...(2.f)}$$

Fig. 1 shows the stress state at the wall of a vertical well and the transformation of these stresses in case of an inclined well.

The data shown in **Table 1** was used to investigate the effect of mud weight and well orientation on the stability of inclined boreholes. Using **Eqs. (1)** and **(2)** the state of stress acting on the borehole wall can be calculated for any orientation. When the horizontal principal stresses are assumed to be equal, the induced stresses are distributed equally around the borehole wall. Under the assumption of Homogeneous Isotropic Linear-Elastic Conditions (HILE), the induced stresses around the borehole are calculated as a function of borehole inclination, wellbore pressure, pore fluid pressure and in-situ principal stresses. If the material surrounding a borehole (assumed to behave in a HILE manner) is stressed beyond its elastic limit, failure will occur at the wall of the hole. Therefore, to asses the stress state required to induce failure, it is necessary to have an understanding of the redistributed (induced) stresses which act on the borehole wall. Using **Eq. (1)** the stress state components acting on the wall of vertical well can be calculated. For inclined boreholes it is necessary to transform the principal in-situ stresses into the coordinates frame of the well as shown in **Fig. 1.b.** This can be accomplished by mathematically rotating the principal stresses using the transformation set of **Eq. (2)**.

EFFECT OF MUD WEIGHT

Among the factors which may be controlled during drilling of an oil well are the mud weight and the orientation of the wellbore. To investigate the effect of mud weight on the stresses acting on the borehole wall, **Eqs. (1)** and **(2)** were applied. In this analysis the effect of both low and high mud weight in wells of various inclinations was examined. A horizontal to vertical principal stress ratio was assumed to be 0.8:1.0. The horizontal principal stresses σ_H and σ_h were assumed to be equal, Thus the induced stresses are distributed equally around the borehole. The result of this analysis are presented in **Figs. 2.A** and **B**. It can be seen that trends of the respective curves illustrated in both figures were identical, the only effect of varying wellbore pressure (mud weight) was to vary the magnitude of the respective values, i.e. the respective curves were moved either up or down the induced tangential stress axis. **Fig. 2.A** illustrates the induced tangential stress which would be concentrated at the borehole wall if a low mud weight is used in well inclinations between 0^o and 90^o. As expected the effective tangential stress acting on a wall of the vertical well was found to be constant around the borehole, as was the radial stress. For inclined wells, however, the tangential (hoop) stress was observed to vary around the periphery of the hole and had a maximum value at an angular position of 90^o (i.e. the σ_x direction) and a minimum value at 0^o (i.e. the σ_y direction). **Fig. 2.B** shows the effect of using a high mud weight in boreholes of the same inclination. It can be seen that the radial stress increased in value (equivalent to the mud weight) while the respective tangential stress reduced in value. This confirms that inclined boreholes are more likely to fail in tension than vertical wells. **Figs. 3.A** and **B** represents the same case discussed above but for unequal in-situ horizontal stresses. It can be seen from **Fig. 2** and **Fig. 3** that, when the in-situ horizontal principal stresses are unequal, the stresses induced by drilling out the supporting rock during drilling operations become more complicated and are greatly dependent on the angular position.

EFFECT OF BOREHOLE ORIENTATION

Fig. 4 shows how boreholes drilled parallel to the minimum horizontal in-situ principal ($\beta = 90^o$) stress are more stable than those drilled parallel to the maximum horizontal principal in-situ stress ($\beta = 0^o$). These results explain the experimental results obtained by Addis et al [6]. It is clear that the induced stress increases as the borehole inclination (α) increases, thus it can be noticed that:

(i) Boreholes drilled parallel to the minimum horizontal in-situ principal stress are more stable than those drilled parallel to the maximum horizontal in-situ principal stress.

(ii) The induced effective stresses increases as the borehole inclination increases.

(iii) When the in-situ horizontal principal stresses are unequal, then the distribution of the induced stresses are function of angular position and less stable compared to the equal horizontal stress case.

Borehole shape is very important in drilling and cementing operations. **Fig. 5** shows how the borehole shape is function of the induced stresses generated during drilling. The borehole shape may change from circular to elliptical depending on the stress magnitude and distribution around the borehole. Similar result has been found experimentally by Addis et al [6] when sandstone rocks were tested under an anisotropic in-situ stress state.

FAILURE CRITERIA OF INCLINED BOREHOLES

The general instability of a borehole is dictated by the difference between the maximum and minimum stresses acting on the borehole wall, i.e. (induced tangential stress - induced radial stress). The region where this difference is greatest experiences the onset of compressional failure. From the examination of **Figs. 2** and **3**, it can be seen that (induced tangential stress - induced radial stress) is greatest for the high angles of inclination (α) and at an angular position of 90^{o}. This effect is more apparent when low mud weight is used. This confirms that inclined boreholes have a reduced ability to resist compressional failure. From the above analysis, assuming normal in-situ stress conditions, it is apparent that compressional and tensile failure will be initiated at 90^{o} to each other. Therefore, when assessing the state of stress around the well, the respective maximum and minimum limiting values must be used as input parameters for the failure criteria. The Mohr's circle approach is an ideal method to illustrate in graphical terms the stress relationships at the borehole wall brought about by varying the wellbore pressure. To construct a Mohr's circle using polar coordinates, the effective radial and hoop stresses are plotted on the x-axis and a circle is drawn through these points with the centre midway between them. The top of the circle represents the maximum shear stress. **Figs. 6** and **7** show how the stability of a borehole is function of borehole orientation and the magnitude of the in-situ stresses. This effect might appear clearer when plotting the induced stresses on a Mohr-Coulomb failure mode. Thus boreholes drilled parallel to the minimum horizontal in-situ stress are more stable than those drilled parallel to the maximum in-situ horizontal stress. Another interesting conclusion might be drawn from **Fig. 8** that if the mud weight (wellbore pressure) decreases, the value of radial stress decreases and the hoop stress increases, thus enlarging the Mohr's circle. If the circle bisects a specified failure criterion (envelope), borehole failure in compression will occur. To reduce the radius of the circle and therefore prevent failure, mud weight should be increased. This increasein mud weight will increase the value of the radial stress which will effectively reduce the hoop stress. As a result of this, the circle becomes smaller and its periphery moves away from the failure curve. Increasing the mud weight too much, however, will lead to the radial stress exceeding the hoop stress. Subsequently, if the tangential stress becomes tensile, the borehole will fail in tension. Thus a fracturing and lost circulation condition will exist. Using the same approach discussed above one can investigate the effect of in-situ stresses. Two cases were considered here, the first was an equal horizontal principal stresses ($\sigma_H = \sigma_h < \sigma_v$), and the second was unequal horizontal principal stresses ($\sigma_H \neq \sigma_h < \sigma_v$). When the horizontal stresses are unequal, the induced hoop stress becomes less in value (at $\theta = 0^{o}$) which means the well will probably fail in tension.

The induced stresses increases as the borehole inclination increases (at $\theta = 90^o$), which means that the hole may fail in compression or shear.

CONCLUSIONS

1- Linear-Elastic model can be used in wellbore stability analysis and it provides a useful information on the influence of mud weight, pore pressure, in-situ stress state and hole orientation on wellbore stability.

2. Borehole stability analysis becomes essential when planing for inclined or horizontal wells.

3. Borehole orientation has a substantial influence on the stability of boreholes drilled in abnormally stresses formations.

4. Boreholes drilled parallel to the minimum horizontal principal in-situ stress was found more stable than those drilled parallel to the maximum horizontal principal in-situ stress.

5. Deviation of borehole shape from circular can be predicted using the Linear-Elastic model.

6. Data obtained from Linear-Elastic model was used as input data for Mohr-Coulomb failure criterion and the mechanical stability of inclined and horizontal wells was predicted.

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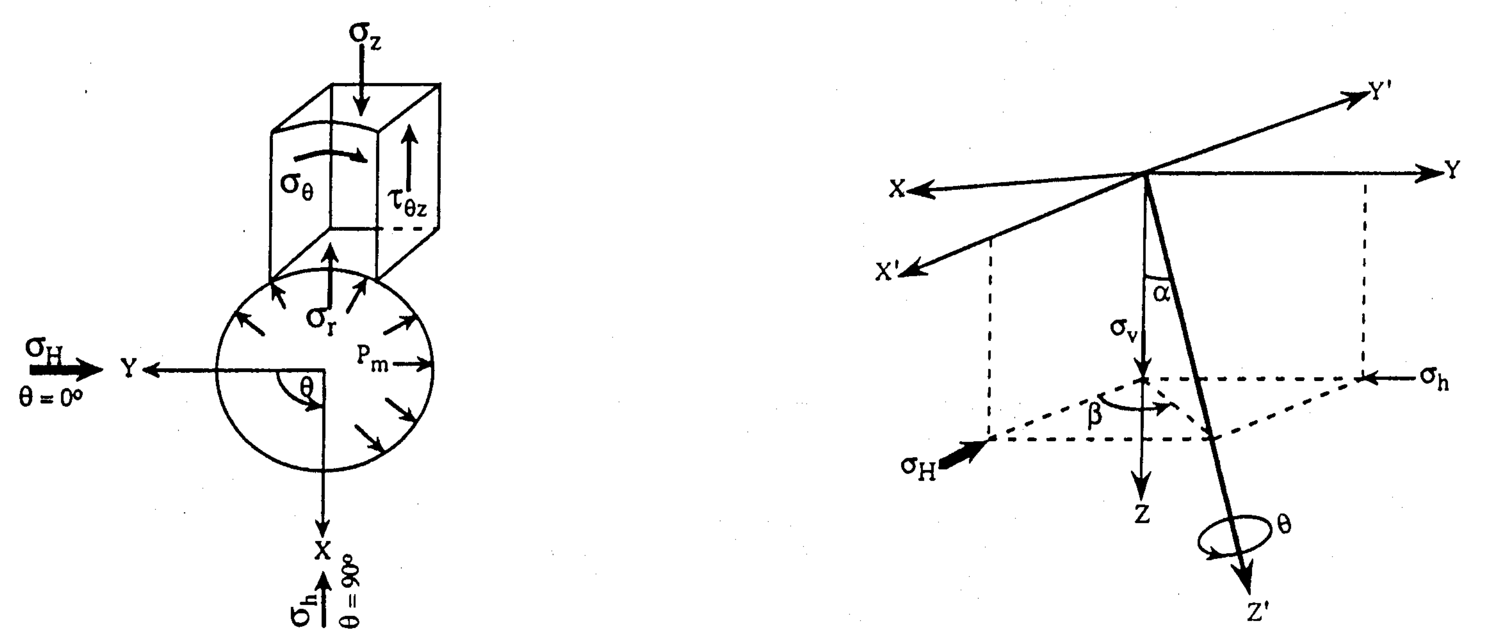
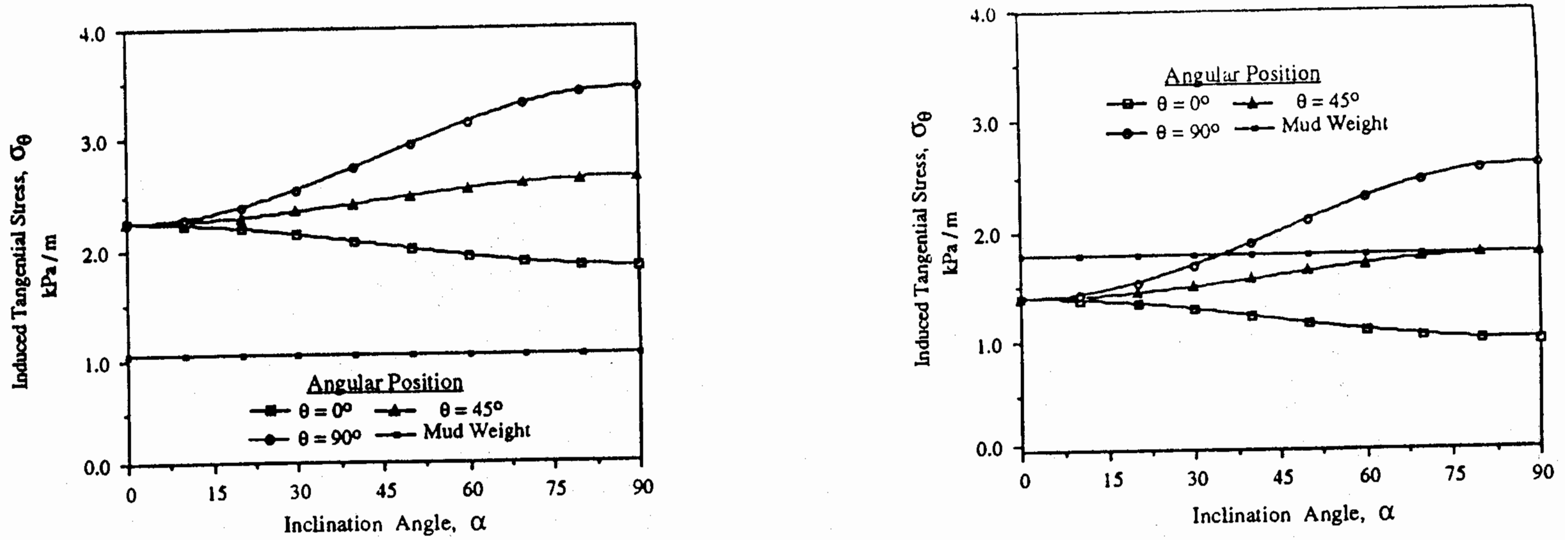
Table 1 : Input Data Used to Investigate the Effect of Well Inclination on Borehole Stability.

Equal Horizontal Principal In-situ Stress State		Unequal Horizontal Principal In-situ Stress State		Borehole Orientation Data	
$\sigma_H = \sigma_h$	= 1.89 kPa/m (0.9 psi/ft)	σ_H	= 1.89 kPa/m (0.9 psi/ft)	α	= between 0^o (Verticl Well)
σ_V	= 2.1 kPa/m (1.0 psi/ft)	σ_h	= 1.68 kPa/m (0.80 psi/ft)		and 90^o (Horizontal Well)
Pp psi/ft)	= 0.966 kPa/m (0.46 psi/ft)	σ_V	= 2.10 kPa/m (1.0 psi/ft)	θ	= between 0^o and 90^o
ν	= 0.25	Pp	= 0.966 kPa/m (0.46 psi/ft)	β	= between 0^o (parallel to σ_H
		ν	= 0.25		and 90^o (parallel to σ_h)



(A) Stress State at the Wall of Vertical Wellbore.
(B) In-Situ Stresses Transformation for Deviated Wellbore.

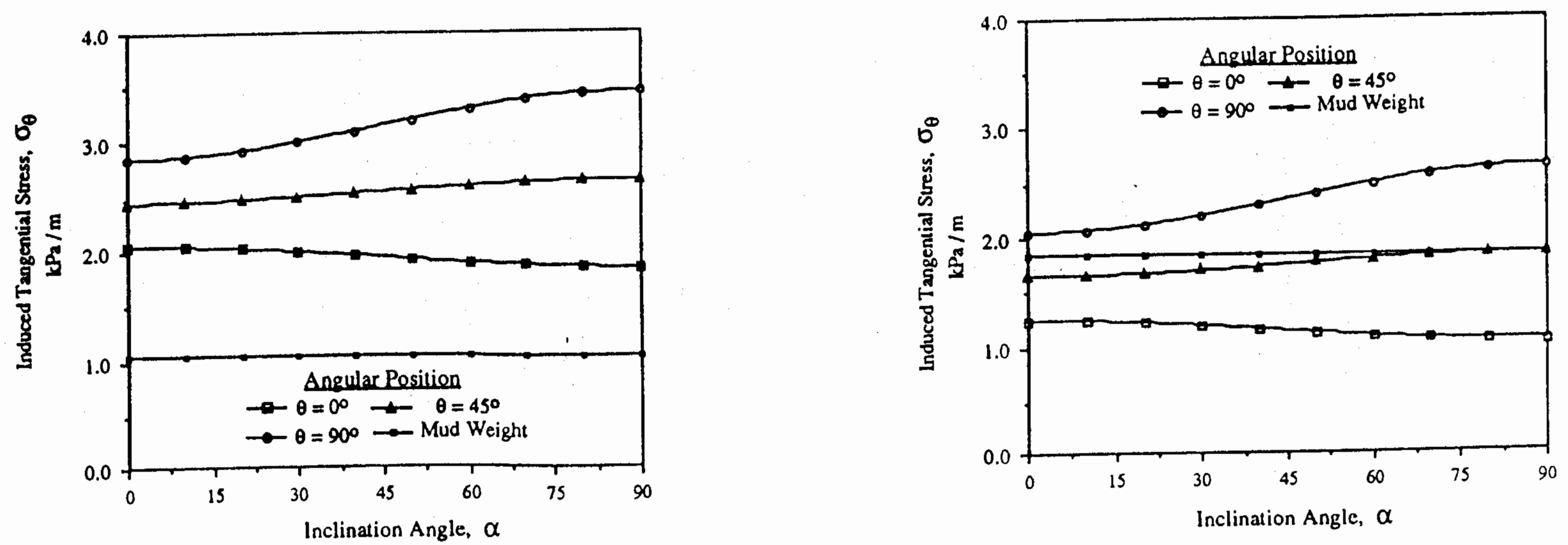
Fig. 1 Induced Stresses at the Wall of an Inclined Borehole and its Transformation into Borehole Frame.



-A- : Mud Weight = 1.05 kPa/m (0.5 psi/ft)

-B- : Mud Weight = 1.89 kPa/m (0.9 psi/ft)

Fig. 2 The Effect of Mud Weight On the Induced Stresses Around an Inclined Borehole for Equal Horizontal Principal In-Situ Stress State.



-A- : Mud Weight = 1.05 kPa/m (0.5 psi/ft)
$\beta = 0°$

-B- : Mud Weight = 1.89 kPa/m (0.9 psi/ft)
$\beta = 0°$

Fig. 3 The Effect of Mud Weight On the Induced Stresses Around an Inclined Borehole for Unequal Horizontal Principal In-Situ Stress State.

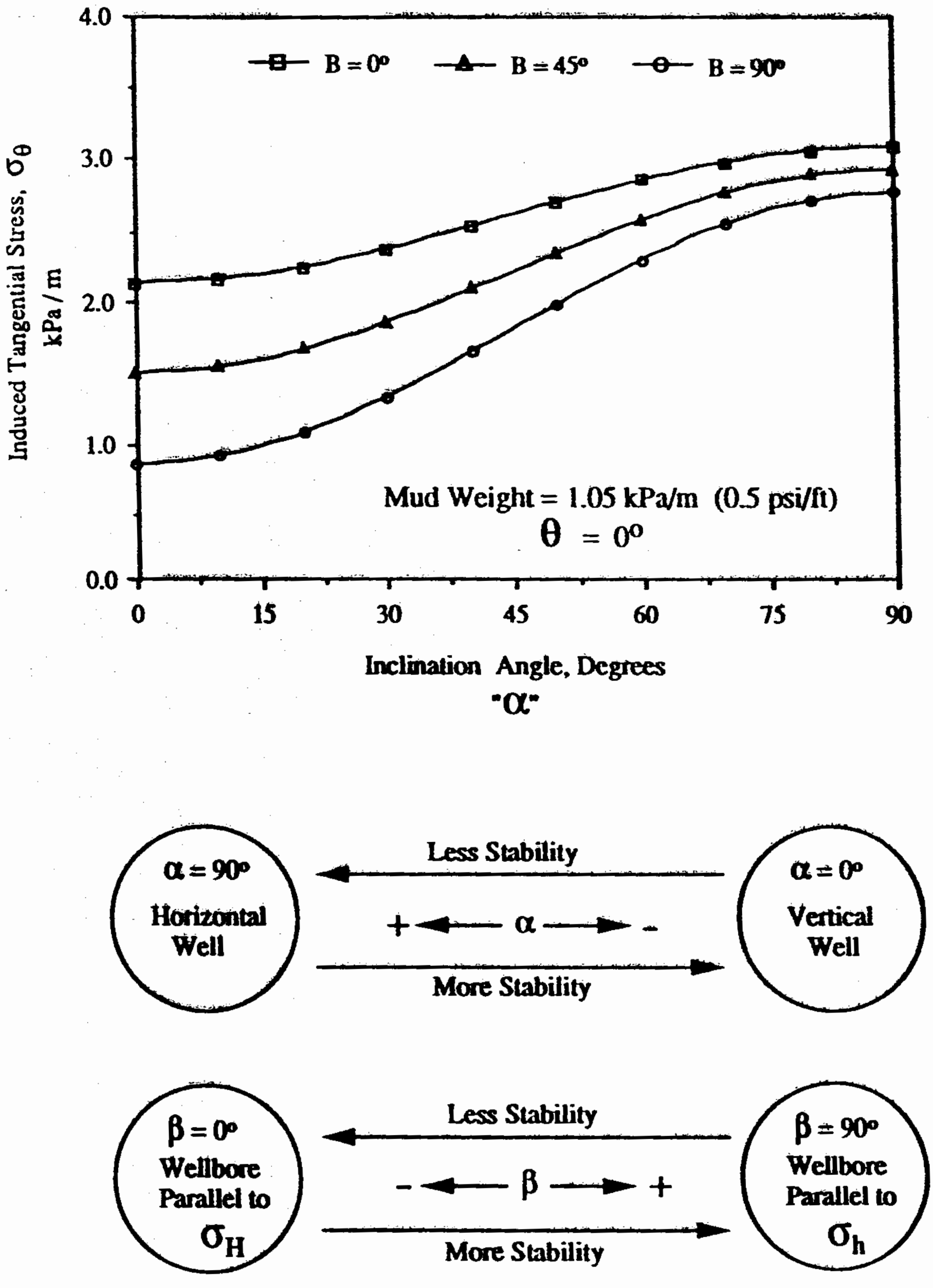


Fig. 4 : The Effect of Well Orientation on Borehole Stability.

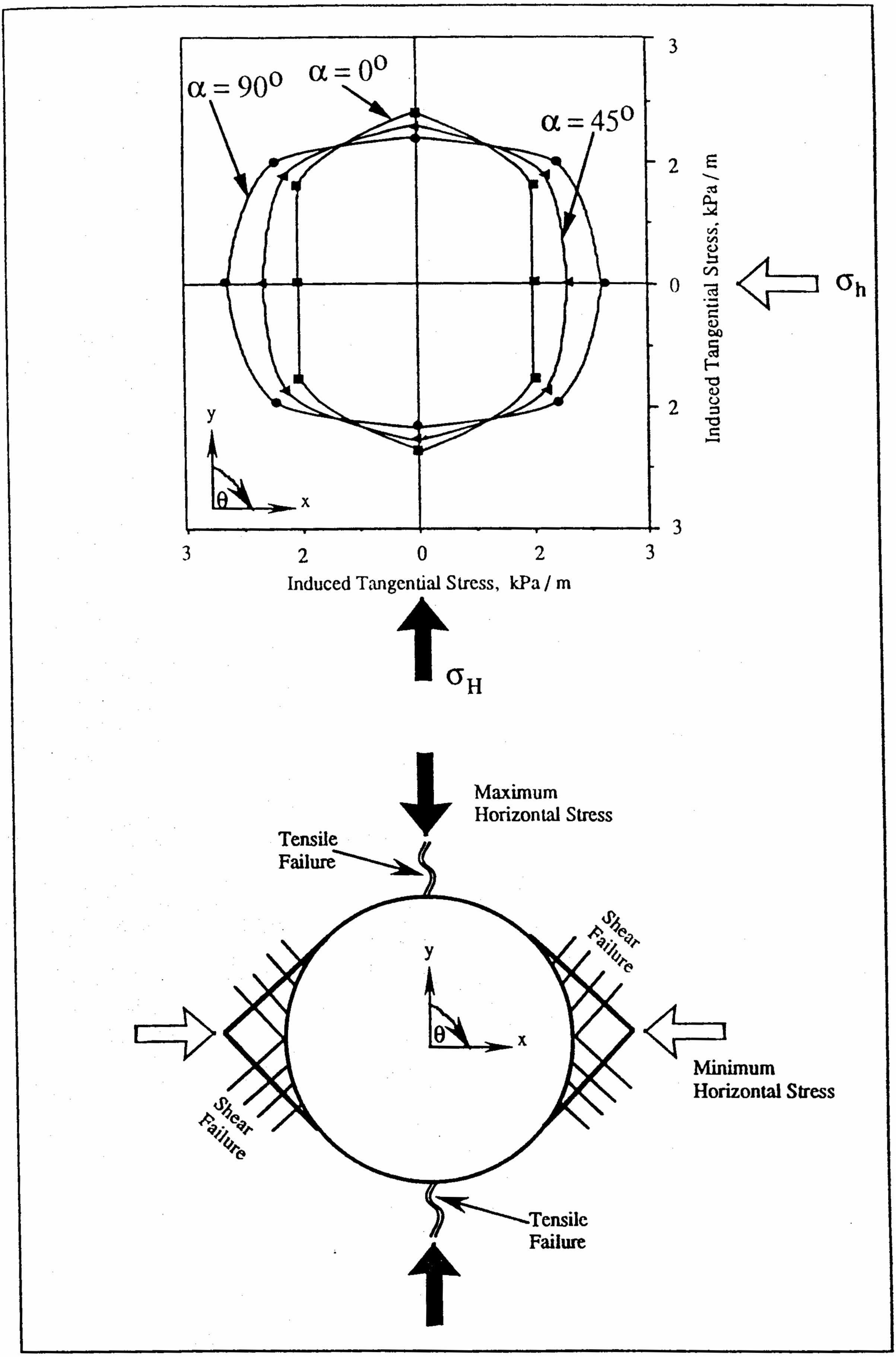


Fig. 5 : Borehole Shape as Function of the Induced Stresses.

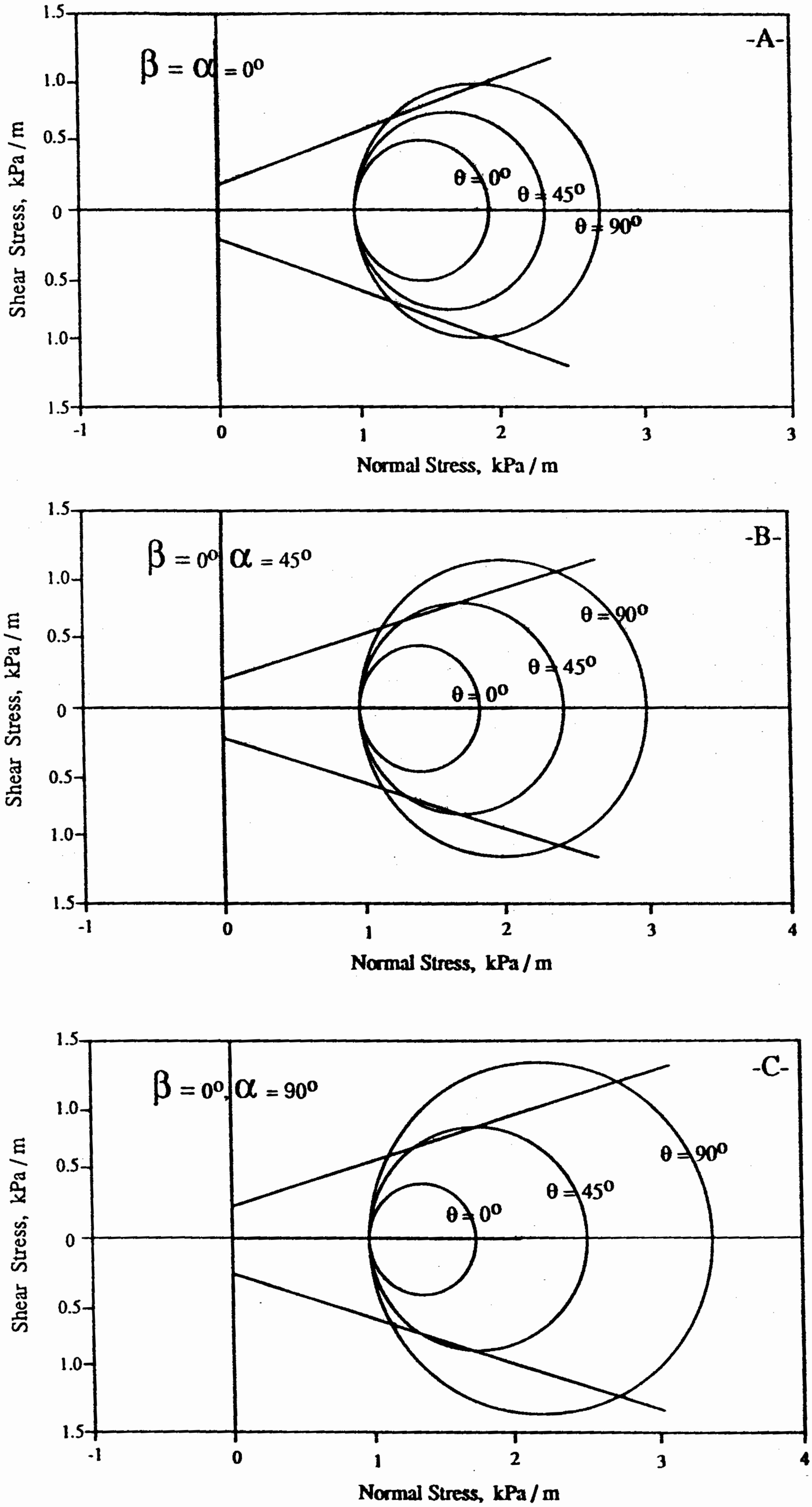
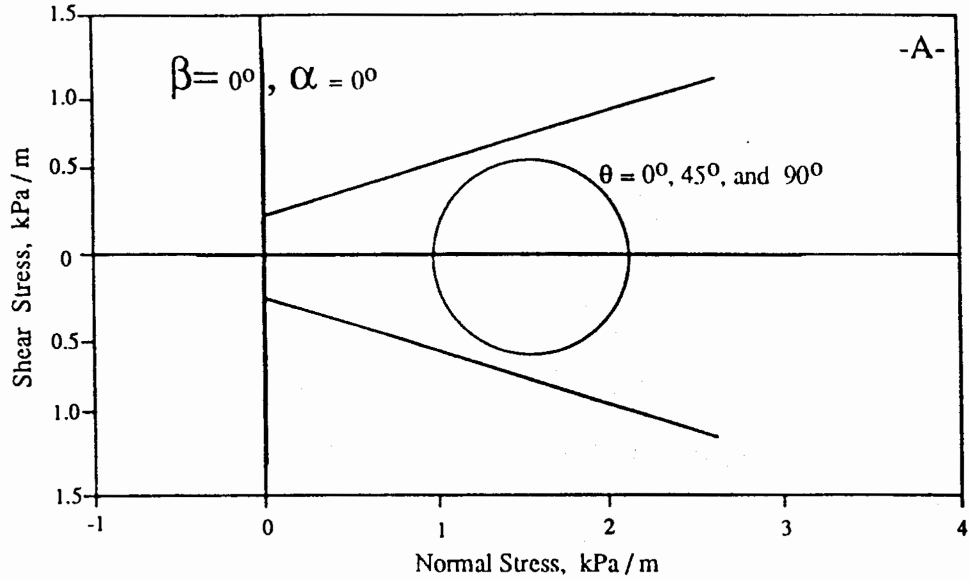
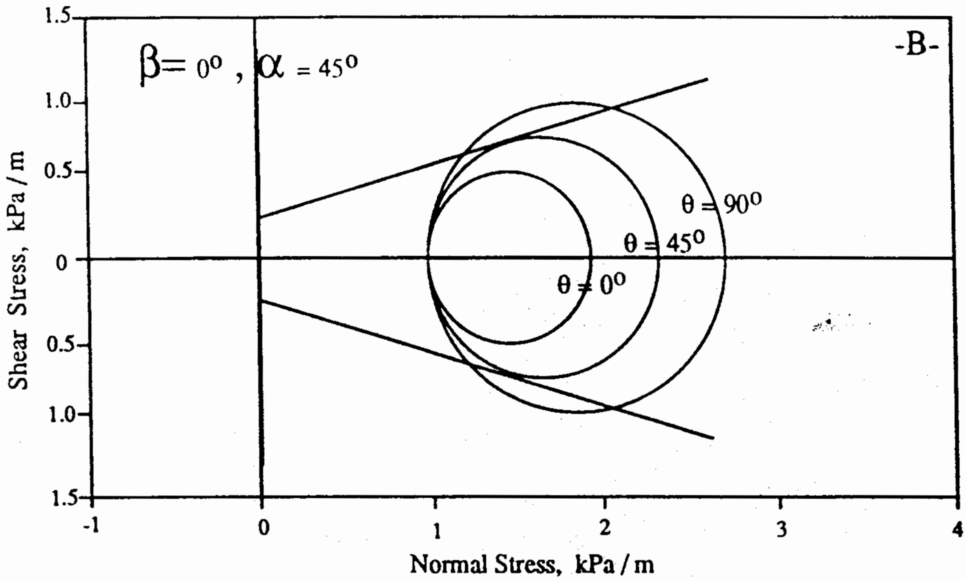


Fig. 6 : The Effect of Borehole Orientation on the Induced Stresses Around the Borehole with Unequal Horizontal In-Situ Stresses and Mud Weight of 1.05 kPa / m.





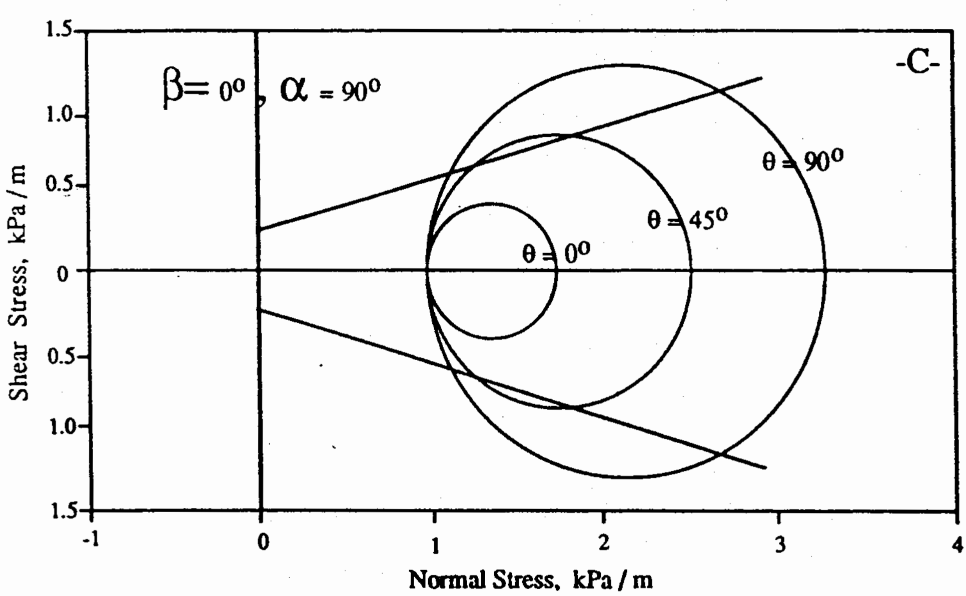


Fig. 7 : The Effect of Borehole Orientation on the Induced Stresses Around the Borehole with Equal Horizontal In-Situ Stresses and Mud Weight of 1.05 kPa / m.

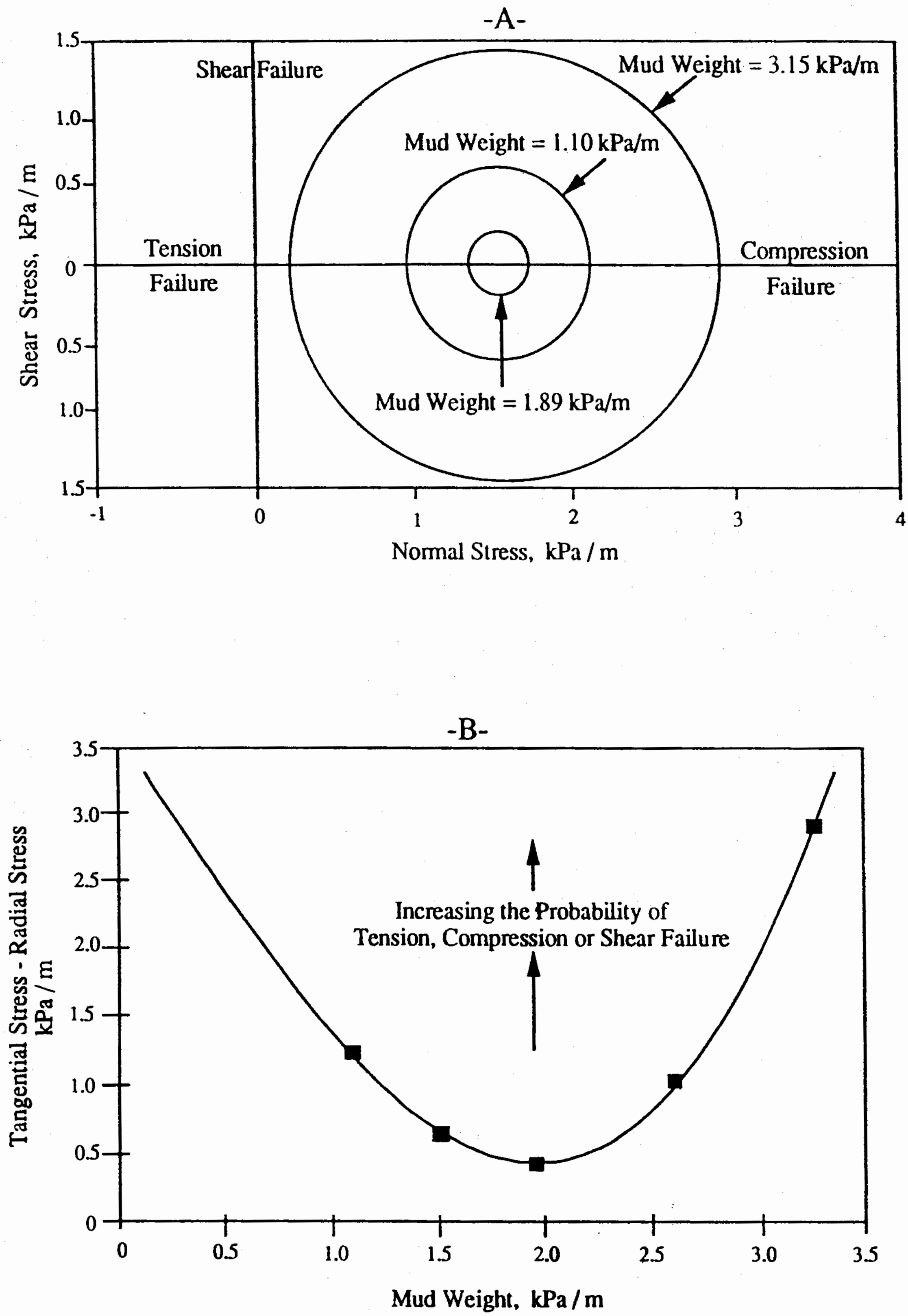


Fig. 8 : The Effect of Mud Weight on Rock Failure Criteria.

$\sigma_v = 1.0$ psi/ft $\sigma_h = \sigma_H = 0.8$ psi/ft $\beta = \theta = \alpha = 0^o$

AEIC' 95

AL-AZHAR ENGINEERING FOURTH INTERNATIONAL CONFERENCE

December 16-19, 1995

FACULTY OF ENGINEERING
AL-AZHAR UNIVERSITY

Nasr City, Cairo, Egypt

VOLUME (10)
PETROLEUM ENGINEERING